Initiating the 2002 Mars Science Laboratory (MSL) Technology Program

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Abstract – The Mars Science Laboratory (MSL) Project is an aggressive mission launching in 2009 to investigate the Martian environment and requires new capabilities that are currently are not available. The MSL Technology Program is developing a wide-range of technologies needed for this Mission and potentially other space missions. The MSL Technology Program reports to both the MSL Project and the Mars Technology Program (MTP). The dual reporting process creates a challenging management situation, but ensures the new technology meets both the specific MSL requirements and the broader Mars Program requirements.

MTP is a NASA-wide technology development program managed by JPL and is divided into a Focused Program and a Base Program. The MSL Technology Program is under the focused program and is tightly coupled to MSL's mission milestones and deliverables. The technology budget is separate from the flight Project budget, but the technology's requirements and the development process are tightly coordinated with the Project.

The MSL Technology Program combines the proven management techniques of flight projects with the commercial technology management strategies of industry and academia, to create a technology management program that meets the short-term requirements of MSL and the long-term requirements of MTP. This paper examines the initiation of 2002 MSL Technology program. Some of the areas discussed in this paper include technology definition, task selection, technology management, and technology assessment. This paper also provides an update of the 2003 MSL technology program and examines some of the drivers that changed the program from its initiation.

Outline

1. Introduction
2. MSL Technology overview
3. 2002 Technology Implementation
   3.1 Technology Definition
        3.1.1   Development Organization
        3.1.2   Project Pre Formulation
        3.1.3   Mapping Requirements to Technology
   3.2 Technology Selection
        3.2.1   Assign Task Managers
        3.2.2   Prepare Task Proposal Presentations
        3.2.3   Task Selection Process
        3.2.4   Technology Development Agreements (TDA)
   3.3 Technology Management
        3.3.1   Element Technical Meetings
        3.3.2   Monthly Management Meetings
        3.3.3   Technology Change Request
        3.3.4   Change Control Board
        3.3.5   Year End Review
        3.3.6   TRCR Process

4. Technology Tools
   4.1 Aggregate Project Plan
   4.2 Technology Funnel Chart
   4.3 Decision Analysis Tools

5. Conclusion

1. Introduction

The Mars Science Laboratory (MSL) Project is an aggressive mission launching in 2009 to investigate the Martian environment. The MSL Project initiated its Technology Program in 2002 while in its pre-formulation phase. This paper examines MSL's plans, developed in 2002, to define and initiate its technology program.

The Mars Technology Program (MTP) is comprised of a *Focused Technology Program* and a *Base Technology Program* [3]. MSL's Technology Program is under the MTP *Focused Technology Program* and is roughly an $80 million effort to develop the technology needed to meet the unique requirements of the MSL Mission.

The MSL mission introduces a number of significant technological innovations. The most important of these are: 1) the ability to make a safe landing at almost any locality on Mars (high altitude and latitude) and 2) the ability to operate an analytical science laboratory on the surface of Mars. These technology innovations carry forward into future missions in the second decade of this century.

The *Base Technology Program* develops enhancing technologies for missions proposed for 2009 and beyond. The Base Program stresses breakthrough technology elements that are not in the critical path of missions. It addresses technology needs that are less mature and higher risk (and higher payoff) than those constituting the Focused Program.

2. MSL Technology Overview

MSL is the first mission with an onboard science laboratory that performs in-situ analytical experiments. In addition to being a full science mission, MSL will also provide technology feed forward to future missions that require the ability to land large payloads on Mars such as a Mars Sample Return mission. The MSL mission, with its goal of a 500 sols (Martian days) mission life, is defined to be a long-life mission.

From a technology point of view, there are two main technology areas that are required to be developed for the mission. One is the Entry, Descent, and Landing (EDL) capability and the second is Surface System technologies. Surface system technology includes rover technology, long-life systems, and onboard sample preparation and distribution experiment. The following paragraphs describe these technology developments.

2.1 Entry, Descent and Landing (EDL)

One of the main goals of the MSL technology program is to develop the capability to land safely near any chosen site (including higher elevations) in order to provide a near global access to Mars. To achieve this ability to land safely at any locality on Mars, the entire process of entry, descent and landing was reviewed and innovations are planned to provide the needed capabilities. Figure 2-1 shows the EDL technology goals.

Past Mars Mission utilized radio-based approach navigation, no control of the lift vector during entry, a single stage parachute, and hazard tolerance only to the extent that either airbags or landing struts are utilized. There was no hazard detection/avoidance capability. Variants of this approach were used on Viking and Pathfinder and will be used on the Mars 2003 mission (MER). The errors in approach navigation propagate through the trajectory, resulting in a landing error ellipse ranging from 100 km cross range to 300 km along the downrange vector. The payload mass that can be delivered using existing or anticipated launch vehicles with this system is limited to ~ 70 kg.
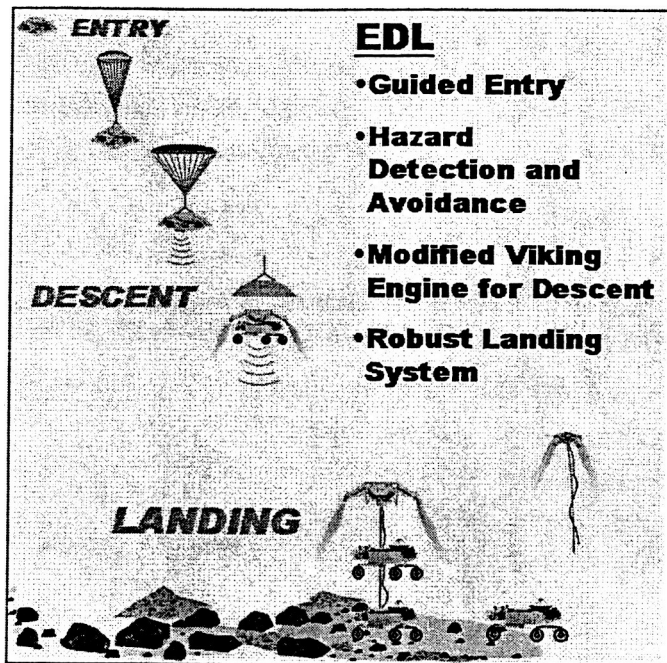

Figure 2-1 – MSL's EDL Technologies Goals.

Precision landing reduces the risk of encountering hazardous areas such as large craters and steep canyons at any given region of Mars where it is desired to land. The goal of MTP is to develop new technology to reduce the landing error ellipse to smaller than 3 x 10 km. In addition the payload mass will be raised to ~ 300 kg. To achieve this goal, each step of the EDL process is upgraded with new technology. Each step is developed with advanced technology, with systems integration used to assure that all the pieces fit together. To achieve this goal, three complementary technologies are being developed: 1) Precision landing, 2) Hazard avoidance, and 3) Robust landing.

Precision Landing – A lifting entry vehicle is being developed with L/D ~ 0.25 (lift/drag) that is capable of actively guiding itself from entry to parachute deployment despite uncertainties in the entry conditions, atmospheric density profile, winds and aerodynamic performance. The two-stage parachute system includes a supersonic chute and a subsonic chute. Improved descent propulsion will be achieved by recapturing Viking technology with new improved components.

Hazard Detection and Avoidance – Hazard avoidance provides an "eyes wide open" capability at landing. The overall process is illustrated in Figure 2-1. This makes it possible to make adjustments to the landing location to avoid large craters, large rocks and steep local slopes. MSL is developing an

integrated terminal guidance, navigation, and control system that predicts the descent flight path after the subsonic parachute is deployed, detects hazards such as rocks and slopes using active sensors, and after jettisoning the parachute, steers the lander to a safe landing area. A RADAR sensing system for 0-7 km altitudes is in development to generate initial terrain maps and create initial estimates of the landing area at ~ 7 km altitude. This system provides more time for the lander to be laterally maneuvered to avoid undesirable landing sites.

Robust Landing – Once landing is committed to, this technology makes it possible to tolerate the unexpected or provide resilience to failures in either precision landing or hazard avoidance systems. The baseline plan is to get away from the landing pallet system and all its mass, egress, and design problems and develop a skycrane system that is less complex and provides better technology feed forward capability.

2.2 Surface System Technologies

These technologies include all the technologies that enable a rover to travel long distances, place instruments autonomously, and analyze samples in its onboard laboratory. The rover and its instrumentation must last at least 500 sols (Martian days).
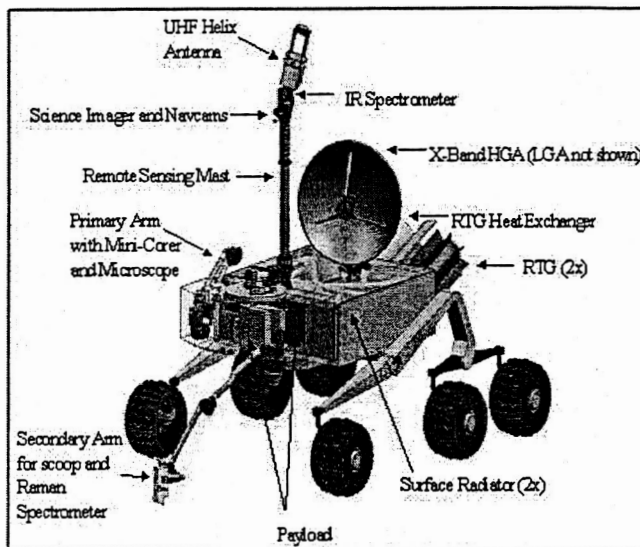

Figure 2-2 – MSL's Surface System Technologies.

Improved rover autonomy is developed to enable safe navigation as well as autonomous science operations for Mars surface missions. The strategy is to integrate technologies from MTP's Base Program that are competitively selected and integrate them to demonstrate the capabilities that are required for MSL. The Base Program is developing technology for the on-board capability to potentially negotiate relatively long distances without supervision from the Earth during traverses from one exploration site to another. The time delay inherent to Earth-Mars communications makes it impractical to carry out long traverses with Earth supervision. New instrument concepts will be integrated with rover platforms. These technologies will be fully tested and validated with full-scale remote terrestrial field trials in simulated Mars terrain, including simulated science operations. Comprehensive control architecture is being developed for autonomous rovers that capture the state of

the art in robotics and autonomy software. This system is distinguished by its layered structure using object-oriented hierarchies.

Long Life – A study was conducted to determine which of the rover components are likely to fail during the 500 sol mission and it revealed that there are major weaknesses in the area of mechanical systems, particularly motors and bearings. Another major area was the electronics which would be exposed to the extreme Martian temperature fluctuation. MSL has a Thermal Cycle Resistant Electronics (TCRE) task to test potential hardware under realistic conditions.

Sample Processing and Distribution Experiment (SPADE) – One of the main differences between MSL and past Mars missions is MSL's capability to analyze Martian samples onboard its analytical laboratory. The laboratory consists of science instruments, sample acquisition, processing, and distribution system.

The objective of the Sample Processing and Distribution Experiment (SPADE) system is to crush rocks (0.1-1 mm) and distribute them to various onboard science instruments. Cross contamination for this type of a system is a major concern. A technology requirement has been established to insure that no more than 5% contamination results from one sample to the next. This number can be decreased by processing the second sample more than once, thus reducing the contamination to levels below 5%.

The previous paragraphs provided an overview of the technologies needed for the MSL Mission. The following sections describe how MSL and MTP defined, selected, and managed the specific technologies need by MSL.

3. 2002 Technology Program Implementation

The purpose of the MSL technology program is to retire technical risks while the project is in formulation and before it enters implementation. If a technology risk cannot be retired before implementation, the project still has time to select another technology and modify their mission concept. The technology program matures the most effective technologies while balancing each technology's performance, cost, risk, and schedule. During the technology program, MSL matures the required technologies from their present Technology Readiness Level (TRL) that is typically between TRL 2 and 3 to a TRL 6.

TRLs are a systematic metric/measurement system that supports assessments of the maturity of a space technology and provides a method of comparing maturity between different types of technology. The TRL scale is from 1 to 9, where 1 represents a technology principle and 9 represents a technology flown successfully in space. Projects that are not technology demonstration missions typically don't accept the risk of including a technology with a TRL of less than 6 in their design concept. TRL 6 corresponds to a technology functioning in a subsystem (model or prototype) in a relevant environment (ground or space).

NASA's guidelines for Project Management, NPG 7120.5B, states:

The purpose of the formulation subprocess is to define a project concept and plan for implementation to meet mission objectives... The formulation subprocess ... assesses the technology requirements and develops the plans for achieving the technology options ... [1]

The following sections describe how MSL defined its project concept, assessed its technology requirements, and developed its technology implementation plan.

MSL's technology implementation process, show in Figure 3-1, include three major stages: technology definition, technology task selection, and technology management. The following sections describe each of these efforts and relate them back to Figure 3-1. Figure 3-1, MSL Technology Implementation Plan, also lists the paragraph numbers of the following sections to show how the flow of the paper corresponds to the flow of the technology implementation process.
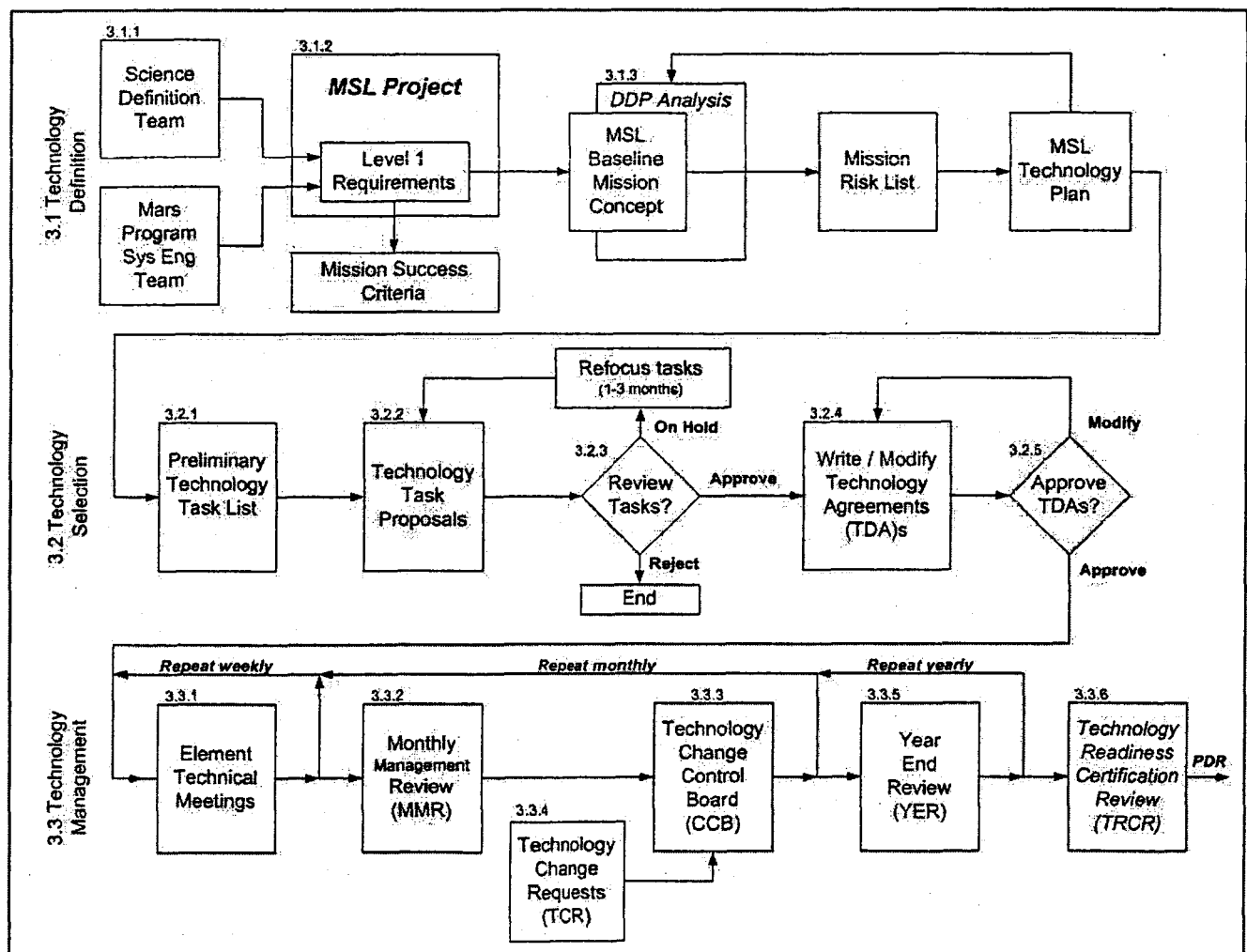

Figure 3-1 – MSL Technology Implementation Process

3.1 Technology Definition

The first stage of MSL's technology implementation process is *Technology Definition*. In this stage, as described below, the different organizations work together and produce science requirements, a mission concept, a mission risk list, and a list of candidate technologies that reduce the mission risks.

3.1.1 Development Organization

Central to implementing a successful technology program is an effective organization structure. The following section describes the 2002 MSL organization (shown in Figure 3-2) that defined and initiated the MSL technology program. The positions in this organization chart will be referred to as the implementation process is described. The roles and responsibilities of each position in the organization are described below.
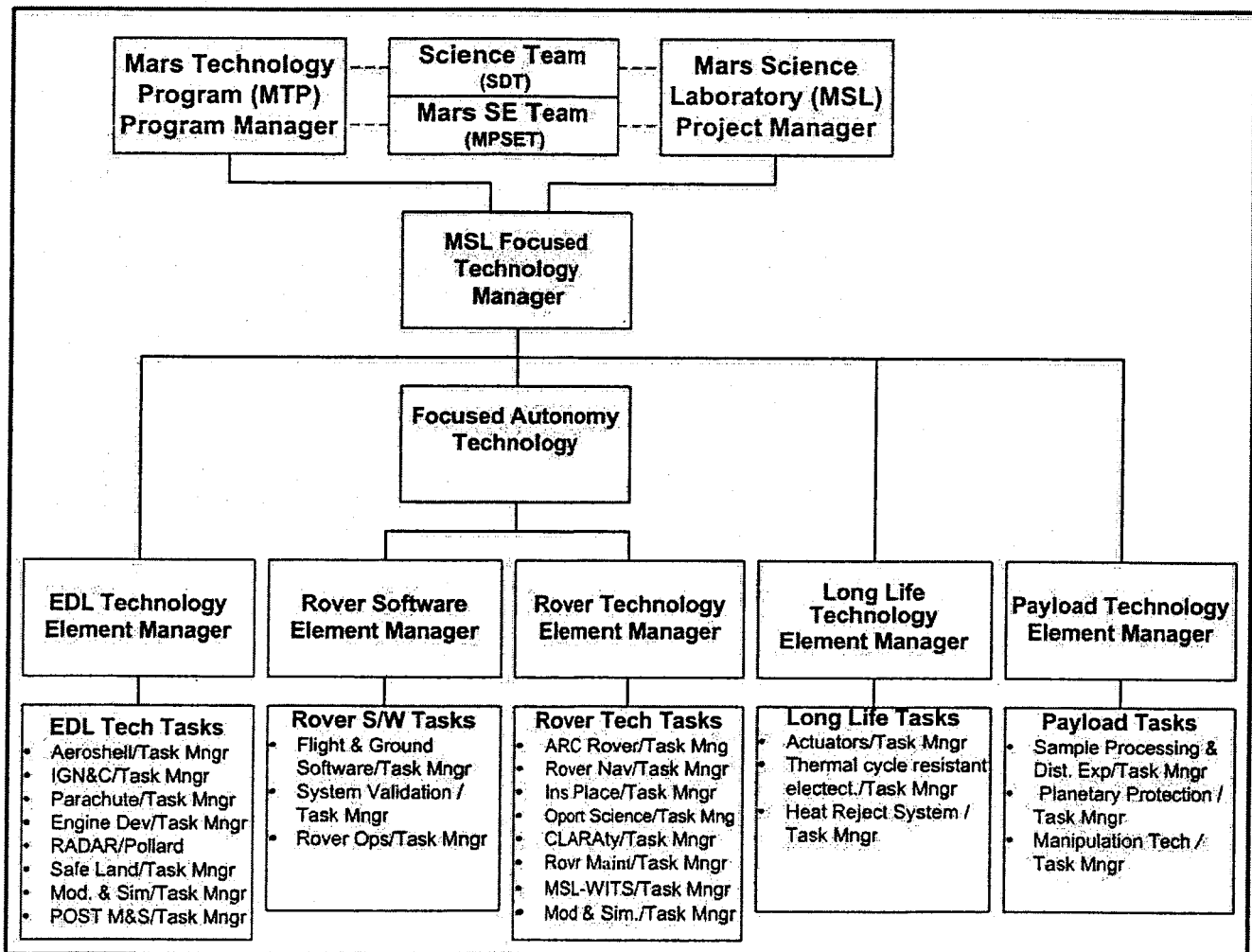

Figure 3-2 – MSL 2002 Technology Organization Chart

At the top and center of this chart are the Science Definition Team (SDT) and the Mars Program System Engineering Team (MPSET). The SDT defines and prioritizes the science goals, objectives, investigations, and measurements of MSL. The SDT ensures that the MSL science requirements and mission concept are consistent with Mars Program science themes. The MPSET ensures that the Mars Program is optimized as a whole and not on a basis of project by project. MPSET also works with the Mars Technology Program and constituent projects to maximize the program's technology readiness. If a technology is needed for multiple missions, MPSET ensures that the requirements of both missions are included in the initial development effort. For example, a previous Mars mission (MRO) developed an optical navigation (OpNav) camera and included the requirements of both the MRO and MSL mission in the development process. The minimal cost to MRO is justified by the significant benefit to MSL and the Mars Program in general.

An interesting feature of the MSL Technology Program is the dual reporting structure in the organization chart. The MSL Focused Technology Manager reports to both the Mars Technology Program (MTP) Program Manager and the MSL Project Manager. The MSL Project Manager ensures technology meets the MSL focused requirements and the MTP Program manager ensures technology meets the long-range requirements of the Mars Program. This inherent conflict actually benefits the project and the program by providing a check-and-balance to many budget decisions.

Five Element Managers report to MSL Technology Manager. The Element Managers are responsible for major systems in the project and ensure that the technologies underdeveloped are compatible with the latest mission concept.

3.1.2 Science Requirements and Mission Concept

The first step in technology implementation (Figure 3-1) is to define the technology to be developed. This may sound obvious and simple, but in a large organization with competing views, issues, and priorities, agreeing on technology requirements is a challenging task.

On MSL the process began with the project working with both the MPSET and the SDT to develop the mission science requirements (Level 1). Next, the project manager, element managers, and different working groups transformed these requirements into a baseline mission concept (where 'baseline' implies the concept will change as the both the technology and the project definition matures). The project uses the baseline mission concept to generate the system-level performance requirements. The following sections concentrate on the process of converting the mission concept into an effective technology implementation plan.

3.1.3 Mapping Requirements to Technology

The technology definition process continues by reviewing the mission concept and the system-level performance requirements in informal (peer) reviews, formal reviews, and working group meetings. These reviews and meetings defined the major risks with meeting the system-level performance requirements and identify candidate technologies to reduce these risks.

Mission risks include performance risks, costs risks, and schedule risks. Through MSL's technology definition and selection process, the project initiated technology tasks that reduced risk in all three areas.

MSL then used a process for managing these risks called Defect Detection and Prevention (DDP) [4]. The DDP process has three steps: 1) determine where we want to be, 2) identify what could get in the way, and 3) decide how we will get there. MSL implemented the DDP steps and put their system-level performance requirements in a tree structure to 'determine where we want to be' and captured as trees of potential failure modes 'what could get in the way'. MSL than scored the impacts of these failure modes on the science requirements to prioritize the failure modes. From the list of failure modes, MSL created their initial Mission Risk List.

The third step, 'decide how we will get there', is probably the most challenging and requires the most iterations with the project, program, and cost modeling organizations. Technology investments were assigned to each risk area and the DDP tool captured the estimate of how each risk area was reduced. A 'top down' approach, based on cost models and project experience, was used to estimate the cost of the different technology investments. A 'bottom up' cost estimate is done after a task manager is assigned and this process is examined in a following section.

Each technology investment, constrained by the technology budget, addressed an item on the prioritized risk list. The risks, and their corresponding technology, include performance risk, schedule risk, or cost risk. An example of the three types of risk and their corresponding technology is as follows: 1) current engines don't meet MSL performance requirements so an investment was made in new engines, 2) current operations schedule does not meet MSL extended life requirements so investments were made to improve operations and science collaboration; and 3) the cost (in dollars and mass) to heat external electronics is high so MSL is investing in temperature extreme electronics.

The process to determine which combination of technologies minimize mission risk and should be funded is described in the following sections.

3.2 Technology Selection

The second stage of MSL's technology implementation process was *Technology Selection*. This stage started with a list of candidate technologies and produced detailed implementation plans for each technology task. The MSL technology selection process took five months for most of its tasks and an additional four months to refocus and select the remaining tasks. The *Technology Selection* process is examined in the following paragraphs.

3.2.1 Assign Task Managers

After MSL agreed to a candidate list of technologies, the Mars Program, MSL Project, and MSL's Element Managers selected Task Managers to lead the development effort of each task. These Task Managers are typically technologists with mixed levels of flight project experience. Since MSL is a focused technology effort, these tasks managers are expected to become integral members of the

project team. Element Managers work with each of the Task Managers to ensure projects requirements are meet. The tightly coupled technology/project environment required the technologist to be less autonomous and more driven by project cost, schedule, and performance constrains. This initially was challenging for the technologists accustomed to working independently, but the common goal of a successful flight project helped unify the diverse team members.

3.2.2 Prepare Task Proposals

Using the *baseline mission concept* and the *system-level performance requirements*, each task manager worked with their element manager to develop a presentation that proposed how their task would meet the mission requirements. These proposals were presented to the MTP Program Manager and the MSL Project Team. The presentations described how the task would improve the current state-of-the-art, for what cost, and in what schedule. The following is a detailed list of what each presentation included.

Overview (Quad Chart) – A one slide summary of the proposed task including a representative picture, objectives summary, milestones list, organizations involved, collaborators, outside companies, and a subtask multi-year schedule including funding levels.

Objectives and approach – These slides described the overall task objectives, quantified the current state of the art, and quantified the new performance goals. Explained the implementation approach to meet these goals and include a bottom-up cost summary. The cost summary included the costs for each fiscal year, the rational for the costs, and bases of estimate. In addition, the task's milestones (or accomplishments) were listed for each fiscal year. Also, each institution involved in the task and their role was listed.

Backup data – Included a list of questions to help the reviews assess the impact, risks, and procurements associated the task. These questions included: 1) What is the functional relationship between the technology task and the following mission goals: a) land safely, b) land precisely, c) go to a specific location, and d) maximize science? 2) What are the assumptions, dependcies, and risks associated with the task? 3) If there are outside procurements, a) what size, b) when is it executed, c) is it competitive or non-competitive, and d) what is the acquisition plan?

Receivable / Deliverable Lists – List all the items being received by the task and delivered from the task to what project element. A significant difference between a *focused technology* task and a *base technology* task is the tight coupling of the technology task to the flight project. A flight project is driven by its launch date and other key milestones. A technology task must synchronized its deliverables and schedule to the flight schedule. Each technology task must closely track what items it expects from a flight system or another technology task (i.e. requirements document, concepts document, hardware, software, models, etc). In addition, each technology task must closely track what items it will deliver to a flight system or another technology task. A problem in one task could ripple through multiple tasks and flight systems, so the project must track the dependencies. After a task is selected, the project created an integrated schedule showing all the receivable and deliverables (Rec/Dels) between the technology tasks and flight systems. This schedule was updated and tracked monthly to quickly identify potential problems.

3.2.3 Technology Tasks Review

Approximately thirty technology tasks presented to the MSL Project and the MTP Program in a three step process: project reviews, functional organization review, and program review. The project reviews included three different reviews over a period of two weeks. The first review was an informal walk-through of the tasks to discuss technology requirements and identify major issues. The second review was two weeks later and it was a dry-run to prepare for the third and final presentations to project management. At each review, the technology implementation concept was tuned to the project's requirements and mission concept.

The second step in the task review process was the JPL functional organization review. This meeting gave the functional managers a chance to review what commitments the task managers were making of their organizations. It also provided a forum for the project and the functional organizations to discuss the latest technology requirements and mission concept.

The second step in the task review process was the MTP Year End Review. This four day review, conducted by the Mars Technology Program, included reviews internal and external to JPL and the Mars Program. They provided and independent assessment of the MSL technologies
with an eye on the big

The task review process resulted in three categories of tasks: selected, rejected, and tasks on hold to get refocused. Most tasks were selected, but the review process modified most implementation plans by changing their budget, development schedules, and development process. Tasks were rejected because their modest improvement in the current state-of-the-art did not justified by their requested budget. For example, one task proposed reducing the size and mass of a flight system. However, the cost and risk of the task did not warrant their small improvement.

Several tasks were worthy of selection, but their scope or development plans lacked the necessary details. These tasks were asked to refocuses their efforts, discuss implementation options with internal and external organizations, conduct trade studies, and plan for a delta-review of their task before being funded. Most of these tasks received a low level of funding while they developed their concepts, complete trade studies, and created new implementation plans. Each of the tasks placed on hold were eventually funded, some with a dramatically different scope and implementation plans.

3.2.4 Technology Development Agreements (TDA)

Once a technology task was selected, task managers and their element managers developed Technology Development Agreements (TDA). A TDA is a roadmap of the process to mature a technology from its current TRL to TRL 6. They also contain specific test protocols for each TRL transition as well as the associated costs, schedules, and facilities to achieve each TRL transition. These Technology Development Agreements (TDA) and their related test protocols represent a process that is performance-oriented and paced by the TRL transitions. To maximize the likelihood of

meeting the overall schedule and budget, each technology task was assigned reserve funds to cover unforeseen problems.

A TDA is a web-based technology management tool that captures the technical and programmatic information related to a technology task. NASA Headquarters requires JPL and other NASA Centers to complete an annual technology inventory. TDAs capture the information required by this technology inventory.

The data captured by TDAa are summarized bellow.

Introduction – Describes the technology, assesses the state-of-the-art, and defines the current Technology Readiness Level (TRL).

Objectives – Describes the task's technical objectives and goals. In addition, this field defines the specific mission requirements this task will enable.

Technical Approach – Describes the methodology and approaches to conduct the proposed development. Define the products and/or expected results. Provides information on technology development approaches such as analysis, experiment, field testing, and, if applicable, flight validation.

Significance – Explains in what way this task will contribute to a NASA Mission. Examples are mission enabling, mission enhancing, increasing safety margin, reducing mass, lowering mission cost, etc. Mention possible applications to other missions. Describes the technology's current performance level and what level of performance the new technology will achieve.

Milestones and Deliverables – Identifies the dates when major milestones will be achieved. At least three milestones is required in each fiscal year of the task. The list includes events, dates, and descriptions.

Funding Distribution – Lists the type of budget elements (people, parts, etc), who is being funded, which fiscal year, the yearly totals, and the total to complete. This field is completed after the task manager completes the budget estimate tool (Friendly Front End, FFE). The FFE tool is described later in this section.

Documented Partnerships/Cooperative Agreements – Describes any formal partnerships, cooperative agreements, or other agreements that involve this task. However, proprietary or partner sensitive information are not to be included in this field.

Comments – This field answers the following questions (as appropriate):
1. What is the impact if funding is increased by 20% and decreased by 20%?
2. What are the priorities of the different sub-tasks?
3. What is the task's probably of success and the backup plan if not successful?
4. How is this technology dependent on other development efforts?
5. Can the technology scale for different configurations and what is the impact on mass and power?
6. What are the technology's interfaces are they standard (if appropriate)?
7. Describe any out-of-house efforts related to this task and at what level of funding.

8. What procurements are planned and what is the acquisition plan?

Infusion Plan – Defines the plan for applying the technology developed in this task to a practical implementation. Final implementation includes either a flight project or a ground application.

Reporting Plan – Defines the plan for reporting status/progress on this task to management. This should include task reviews, non-advocate reviews, project review, written reports and publications.

Commercialization Plan – Defines the plan for transferring the technology developed in this task to commercial use. If appropriate, this field identifies the industry partner teaming on the commercialization effort. If the technology has no commercial potential, this field contains a "N/A".

Approval – The TDA sequence of approval is: Task Manager, Element Manager (or Level-1 Manager), Section Manager, and Project Office.

Other members of the project team, including members of the science team, review the technologies at the initial proposal review and the periodic status reviews. After the TDA is approved, the Project implements the technology development task. The TDA is now under Configuration Management (CM) control and any future changes require MSL technology Change Control Board (CCB) approval. The MSL technology CCB is discussed later in this section. TDAs are reviewed at the end of every fiscal year and changes are made to reflect the technology development updates for next fiscal year.

3.2.5   Technology Budget Worksheet (FFE)

Each task is given a fixed amount of money to develop its technology. The TDA captures cost estimate to complete the task including purchases, travel, subcontracts, and manpower. The data for these fields are generated by the Friendly Front End (FFE), a financial spreadsheet tool that collects all the budget information for the technology development task. The FFE permits great detail in the cost estimates and the rates and factors are already incorporated into the FFE. The FFE is used for estimating: Workforce, Procurements & Subcontracts, and Travel/Services. For more information on the FFE, view the training guide at http://rms.jpl.nasa.gov.

Every month, MSL's Project Resource Analysts (PRA) generates financial reports for each technology development task. These reports list the task's actual spending, compares the actual costs to the planned budget, and flags any variances. If a technology development task is under-running or overspending, the task manager must explain the discrepancy at the next MMR and assess the impact to both the technology task and the MSL Project.

3.3 Technology Management

The third stage of MSL's technology implementation process is *Technology Management*. This stage started the technology tasks are approved and continues until the tasks are completed. A task is completed when it reaches a Technology Readiness Level (TRL) of 6, which typically requires three years. The *Technology Management* process is examined in the following paragraphs.

Hawthorn Effect - Improved process data that results from process operators who know their process performance is being measured and exercise more care in the execution of the process than would normally be done.

Individual behaviors may be altered because they know they are being studied was demonstrated in a research project (1927 - 1932) of the Hawthorne Plant of the Western Electric Company in Cicero, Illinois. This series of research, first led by Harvard Business School professor Elton Mayo along with associates F.J. Roethlisberger and William J. Dickson started out by examining the physical and environmental influences of the workplace (e.g. brightness of lights, humidity) and later, moved into the psychological aspects (e.g. breaks, group pressure, working hours, managerial leadership). The ideas that this team developed about the social dynamics of groups in the work setting had lasting influence - the collection of data, labor-management relations, and informal interaction among factory employees.

The major finding of the study was that almost regardless of the experimental manipulation employed, the production of the workers seemed to improve. One reasonable conclusion is that the workers were pleased to receive attention from the researchers who expressed an interest in them. The study was only expected to last one year, but because the researchers were set back each time they tried to relate the manipulated physical conditions to the worker's efficiency, the project extended out to five years.

Four general conclusions were drawn from the Hawthorne studies:

- **The aptitudes of individuals are imperfect predictors of job performance.** Although they give some indication of the physical and mental potential of the individual, the amount produced is strongly influenced by social factors.

- **Informal organization affects productivity. The Hawthorne researchers discovered a group life among the workers.** The studies also showed that the relations that supervisors develop with workers tend to influence the manner in which the workers carry out directives.

- **Work-group norms affect productivity.** The Hawthorne researchers were not the first to recognize that work groups tend to arrive at norms of what is "a fair day's work," however, they provided the best systematic description and interpretation of this phenomenon.

- **The workplace is a social system.** The Hawthorne researchers came to view the workplace as a social system made up of interdependent parts.

For decades, the Hawthorne studies provided the rationale for human relations within the organization. Then two researchers used a new procedure called "time-series analyses." Using the original variables and including in the Great Depression and the instance of a managerial discipline in which two insubordinate and mediocre workers were replaced by two different productive workers (one who took the role of straw boss - see below). They discovered that production was most affected by the replacement of the two workers due to their greater productivity and the affect of the disciplinary action on the other workers. The occurrence of the Depression also encouraged job productivity, perhaps through the increased importance of jobs and the fear of losing them. Rest periods and a group incentive plan also had a somewhat positive smaller effect on productivity. These variables accounted for almost all the variation in productivity during the experimental period. Social science may have been to readily to embrace the original Hawthorne interpretations since it was looking for theories or

work motivation that were more humane and democratic. – Franke, R.H. & Kaul, J.D. "The Hawthorne experiments: First statistical interpretation." *American Sociological Review*, 1978, 43, 623-643.

3.3.1 Weekly Element Meetings

The Element Managers are responsible for organizing and conducting weekly technical reviews of the technologies in their element. The appropriate task managers and the appropriate project system engineers support these weekly technical reviews. Theses reviews discuss the technical progress of the technology tasks, examine the dependencies of the different, and reviews both the impact of technology on the project's concept and the impact of the maturing project concept on the technology.

During the program, the Element Managers track the progress of both the mission concept and the technology development efforts. As the mission concept changes, the technology requirements are updated and as the technology effort makes progress, the mission concept is updated.

3.3.2 Monthly Management Reviews (MMR)

MMRs are organized and conducted by the MSL Technology Manager. The MMR are supported by the line organizations, the Program Office, and collaborating NASA centers. The MMR reviews technical progress (planned v. actual), action items, development issues, development budgets, and deliverable schedules.

The MMR is supported by the project and the functional organizations, but every quarter the MMR is opened to a broader audience. The Project Manager organizes and conducts the Quarterly Reviews in January, April, July, and October of each calendar year, which replace that month's MMR. The Element Managers prepare and present the Quarterly Reviews for their respective technical areas. The participants include MSL Project staff, NASA Program Executives, representatives from collaborating NASA centers, line management, and technology customers (project and pre-project managers).

3.3.3 Technology Change Process

As the MSL technology tasks proceed and as the MSL Project concept matures, changes to the technology tasks are inevitable. In addition, the MSL technology program is managed by both the MSL Project and the MTP Program, each with a slightly different focus. MSL desires to optimize the project and MTP desires to optimize the program. The technology change control process (shown in Figure 3-3) was established to involve all impacted parties in the change process and to balance the health tension between the project and the program.

The change process is initiated when a Task Manager (TM) drafts a Technology Change Request (TCR) from. The TRC is developed with and approved by both the TM's line management and

Element Manager (EM). The line manager and the EM ensure that the change is consistent with project's desire and the functional organizations ability.

The TCR is then evaluated by the Technology Manager and the impact on the project's budget, schedule, and performance is accesses. If the change is significant or the change is controversial, the change is added to the project's lien list and the Technology Manager presents the change to the Change Control Board (CCB). If the change is not significant, it is approved and implemented by the Technology Manager. Significant changes are those that cost more than $20k or impact a schedule by more that one-month and controversial changes are those that potential impacts the project-program balance. The project's lien list are all open technology change requests.

The CCB meets once a month (if required) and examines any open TCRs in a systematic manner to determine its impact on the project's risk, cost, schedule, and performance profile. The CCB ensures that all affected parties are cognizant of the change and have a voice in the decision making process. The MSL Project Manager and MTP Program Manager chair the Change Control Board (CCB) and have authority to approve any changes which do not affect the projects Level 1 requirements. Advisor members of the CCB include the Technology Manager, the Element Managers, and the project Chief Engineer.

The MSL technology program maintains budget reserves to cover changes and other problems with the technology program. The lien list and the technology budget reserves are reviewed at the monthly Change Control Board (CCB) meetings. The CCB balances the projects and the technology program's risk, cost, schedule, and performance. The CCB can decide to approve or disapprove a TCR. The CCB can also decide to keep the TCR open and review it again at the next CCB meeting. Projects are reluctant to spend reserves early in the fiscal year, but later in the year when potential problems are better understood, a lien may be approved.

In addition to reviewing changes, if a technology task is not performing due to cost, schedule, performance, or risk issues, the CCB can decide if the performance and priority of the task, warrant the spending of the technology reserves (budget, mass, power, or schedule) to address these issues. Another option is to cancel a technology task, adopt the current state-of-the-art performance, and fund a more promising effort on the technology lien list. The lien list and the different funding options provide a sense of urgency to the task managers to keep their tasks on track.
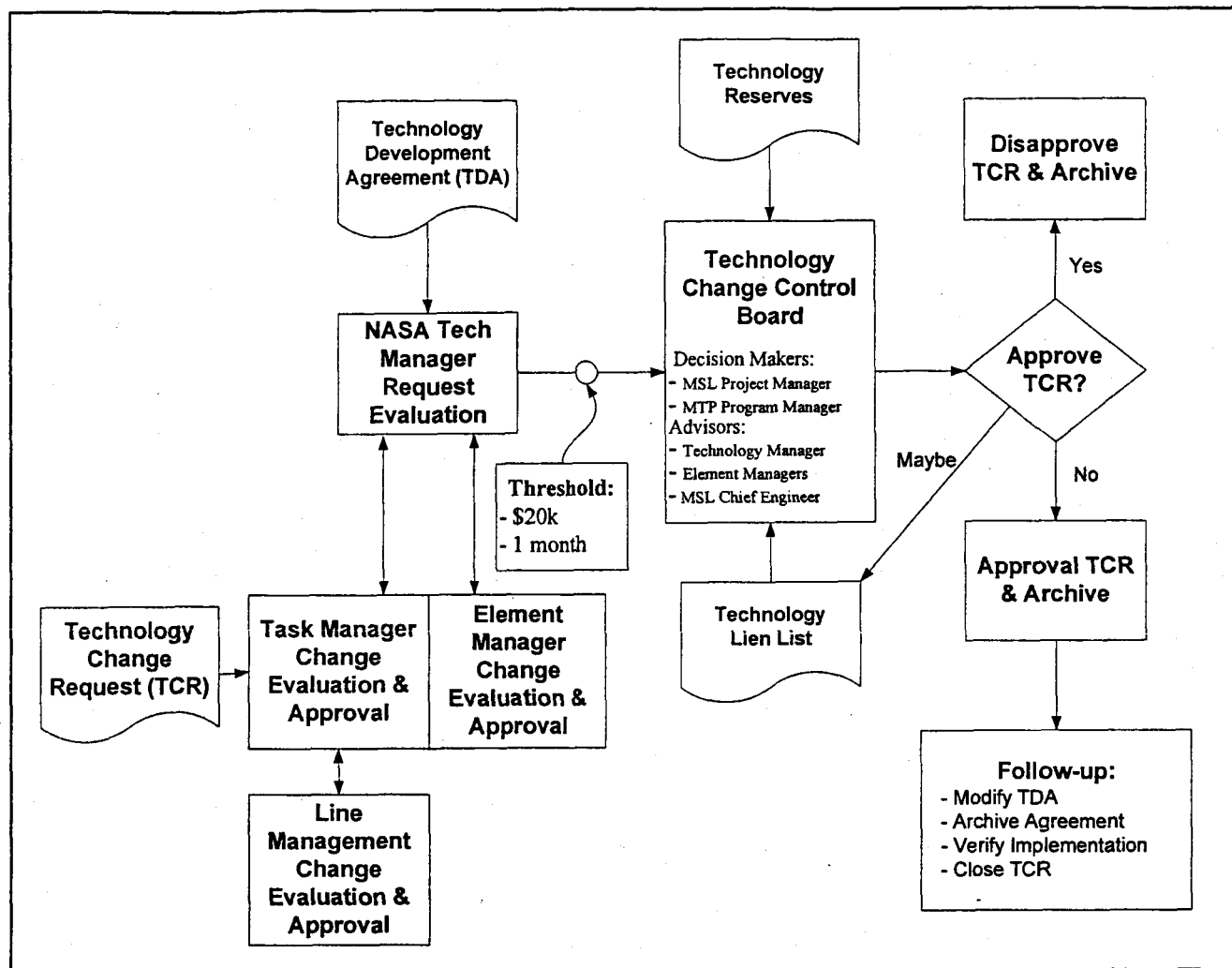
Figure 3-3 – The MSL Technology Change Control Flow

3.3.4 Year-End Review (YER)

The MTP Program Manager organizes an October year-end review and assembles a peer review panel. The panel includes appropriate technical and programmatic personnel from JPL, NASA centers, NASA Headquarters, and universities. The MTP Program Manager or his designee chairs the peer review panel and provide a summary of review results and recommendations to the MSL Project Mánager. The review feedback will be used to improve the technology program by implementing the review panel recommendations as appropriate.

3.3.5 Technology Readiness Certification Review

Traditionally, a major issue with NASA technology programs is there in ability to successfully infuse their technology into flight project. To help solve this, the MSL technology program is a focused program and includes the MSL Project Team in the selection and implementation of the technologies. The infusion plans of each technology are also captured in the task's TDA.

In addition, to help accelerate and simplify the technology infusion process, MSL established a Technology Readiness Certification Review (TRCR) process. In this process, the Task Manager prepares a data package on their technology and presents the package to the project. The package includes the criteria the task used to meet their TRL 6 requirements. For each technology, the TRCR package includes all the design, fabrication, assembly, and test information the project needs to implement the technology.

4. Technology Assessment Tools

The previous sections described the first year of the MSL technology program and defined the processes for defining, selecting, and managing the focused technology tasks. In addition to the processes defined above, the first year of the technology program also implemented a number of technology assessment tools. These tools and their pros and cons are described in the following sections. A change in technology management occurred between the first and second year of the technology program and the tools were no longer implemented. The tools, however, were useful during the first year and warrant a discussion.

4.1 Aggregate Project Plan (Bubble Chart)

For each technology being developed, the aggregate project plan (or bubble chart) maps the technical impact of the technology task against the risk of the task. The chart also includes the budget allocation and budget status of each task. This chart allows managers to quickly assess the status of all technology tasks. A technology portfolio (represented by the aggregate project plan), like a financial portfolio, should be balanced. That is, the risk of developing a technology should be commensurate with the technology's predicted performance or impact. For example, a high-risk technology should have a high impact and a low impact technology better have a low development risk. In addition, if a technology has a high impact, but a low development risk, maybe it should be moved out of the technology effort and into a flight system.

The aggregate project plan is updated every month with the latest status of the technology tasks. The bubble's x/y-location corresponds to the risk/impact of the technology; the size of the bubble corresponds to the task's budget, the color of the bubble corresponds to the task's financial status (red = +/- >10%, yellow = +/- 5% to 10%, green = on budget); and the color of the bubble's ring corresponds to the status of the task's risk/decision analysis assessment. Figure 4-2 is an example of the MSL's technology aggregate project plan.

The following defines the X- and Y-axis of the aggregate project plan:
- *New Core Product* - Fills previously unknown, unmet needs. This is the first introduction of a revolutionary new technology. Stimulates new usage and system designs.

- *New Benefits* - Fills known but as yet unmet needs. Delivers new concepts and benefits that fulfill needs that are otherwise unmet by any technology
- *Improvement* - Better meets needs or meets more needs. This impact is significant, discernible improvement, amplification, or enhancement relative to existing technology benefits.
- *Variant* - Meets same needs differently. This is a minor revision, adjustment, and alterations with relative parity to existing product performance, claims, & features.

Figure 4-1 – A 2002 MSL Aggregate Project Plan (Bubble Chart)

Technology Impact

EDL System Tasks:
1 - Aeroshell - LaRC/ARC
3 - Integrated GN&C
4 - Subsonic Parachute
5 - Engine Development
6 - RADAR
8 - Safe Landing / Pallet System
9 - EDL Modeling & Simulation
10 - POST Modeling & Simulation

Surface System Tasks:
11 - ARC Rover Testbed
12 - Rover Software (MDS)
13 - Rover Autonomy Validation
14 - Long Range Traverse
15 - Instrument Placement
16 - On-board Science
17 - Rover Technology Testbed
18 - WITS on MSL
19 - Rover Operations
20 - Surface Modeling & Sim.
21 - Actuators, Lubs, Bearings
22 - Thermal Cyc Resistant Elec
23 - SPADE Testbed
24 - Planetary Protection
25 - Heat Rejection System (HRS)
26 - Rover Maintenance

BUBBLE COLOR CORRELATES TO BUDGET STATUS: GREEN/YELLOW/RED;
RING COLOR CORRELATES TO DECISION ANALYSIS STATUS: GREEN/RED;
SIZE CORRELATES WITH FY03-05 BUDGET: $1 $2 $3 $4 $5

- *No Change* – This technology meets the same needs with no change. No perceived activity, but involving improved processes that result in cost reductions or meet project/program mandate with no change in quality or other benefits.
- *Radical* - First use of a Technology that is new to the industry
- *Next Generation* - Pushes existing Technologies into a completely different application
- *Incremental* - Extends existing Technologies beyond the normal application
- *Base* - Exploits current standard Technology without extending the range of applications

4.2 Technology Funnel Chart

Funnel Chart – The technology funnel chart maps the high-level project schedule against the schedule status of each the technology tasks. It also captures the budget allocation and schedule status of each task. The funnel chart defines the separation between different technology development stages. The process provides a clear criteria for a technology to proceed to its next development step. It also provides a way to kill technology development efforts that are not performing technically, financially, schedule-wise, or in risk reduction. The funnel chart enables program and project managers to engage technologists at the right time to correct technical and programmatic issues before they impact the project. It also provides a continuous process to verify that the technology fits with the project and program strategy and system architecture. The overall shape of the funnel chart implies that some technology tasks are eliminated as the project refines its implementation concept and some technology tasks cannot meet their requirements.
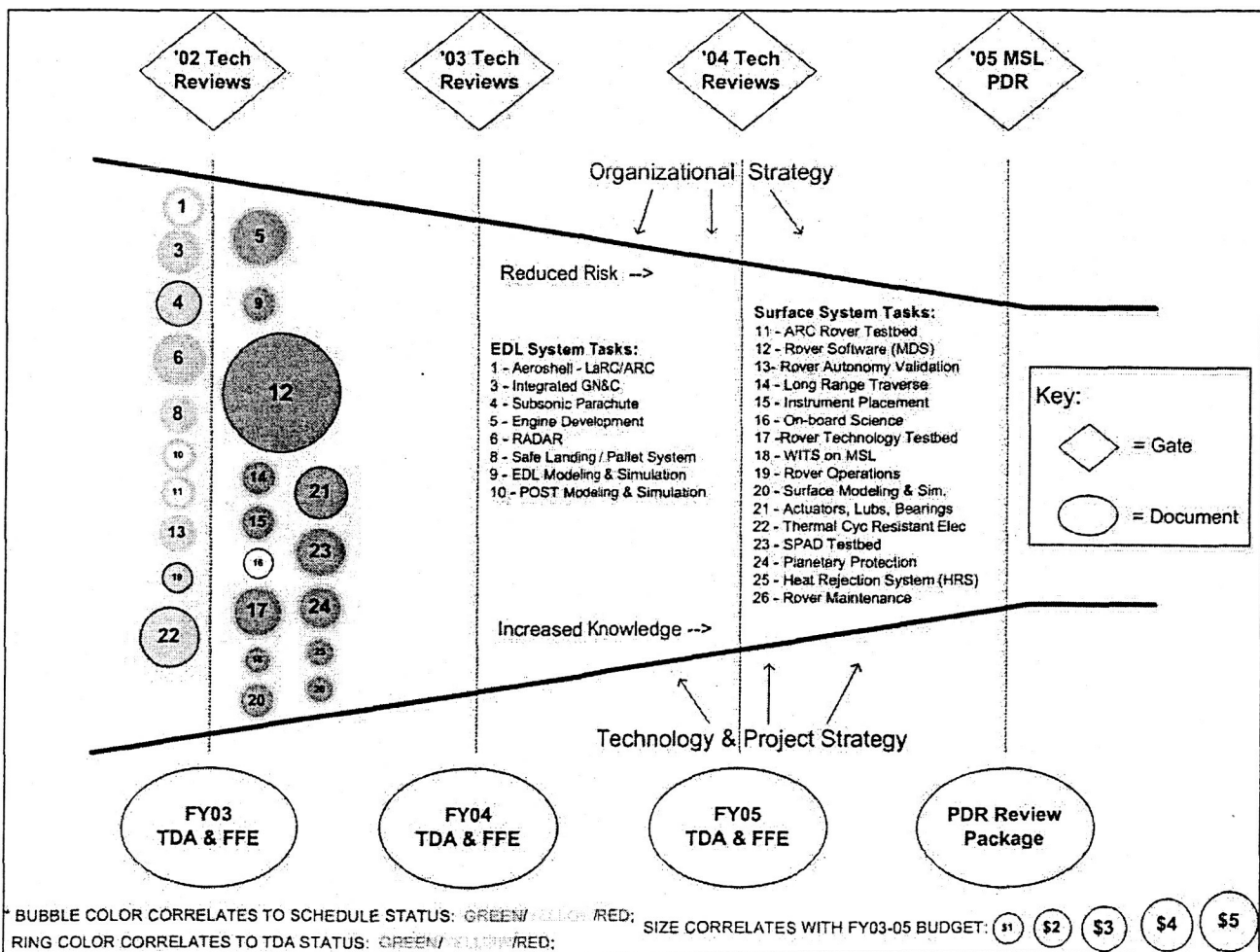

Figure 4-2 – A 2002 MSL Technology Funnel Chart

The primary gates (represented by horizontal diamonds) on the funnel chart are the yearly non-advocate reviews and the quarterly program reviews. These gates give technologists the freedom they need between gates to develop their technologies. This phased gate model facilitates a common understanding of technology task progress. The gates allow the project to defined, track, and review

tasks according to predetermined decision criteria. They also give a project visibility across tasks and elements with standard terminology and simplified reporting. The selection criteria for a task to pass from one phase of the funnel chart to the next include: are key project needs identified and met; will the technology be delivered within budget, schedule, and risk constraints; and does the technology fit the project architecture.

The ovals in the bottom of the funnel chart represent the documents the technology tasks develop to describe their tasks. These documents include the TDA and FFE, which reflect the detailed technical description of the task and the budget required to meet the technical requirements. The TDA and FFE's are periodically update to reflect the latest status of the task. Significant changes to the TDA and FFE require approval by the MSL technology CCB to properly assess the impact of any changes.

Figure 5-2 is an example of the MSL Project's technology funnel diagram and the MSL Project will develop a similar chart when its technology program is initiated. The funnel chart is updated every month with the latest status of the technology tasks. The bubble's x-location corresponds to where the technology is on the TRL/progress scale; the size of the bubble corresponds to the task's budget, the color of the bubble corresponds to the task's schedule status; and the color of the bubble's ring corresponds to the technology's TDA status.

4.3 Decision Analysis Tools

The MSL Project uses a collection of Decision Analysis (DA) and Risk Assessment (RA) tools to manage the decisions and risks associated with MSL's technology development program. One example of these tools is the decision tree. The decision tree captures and analyzes the key decisions associated with each technology task and the decisions that may impact other technologies and the project. A typical decision tree is in Figure 4-3 and the decision analysis associated with this figure will be completed for the critical decisions associated each of the technology development tasks.

Decision trees and the decision analysis process collects the critical decisions of the technology program; defines the performance, cost, and risk of each decision option; and establishes a date when the decision has to be made. The decision analysis process will ensure that the MSL Project makes intelligent and timely technology decisions.
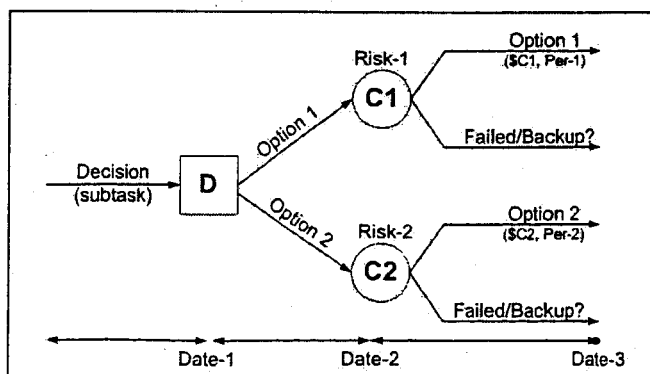

Figure 4-3 – The Decision Tree Analysis Tool

In addition to the decision analysis, the MSL Project will complete a risk assessment of the key technology deliverables. Figure 4-4 is an example of a deliverable's risk assessment. The performance, cost, risk, and date of each critical deliverable will be defined. If the risk of a technology's deliverable is high, a backup option will be defined. For these critical deliverables, the development schedules of the primary and backup options will be compared and if necessary, a parallel technology development effort will be initiated.
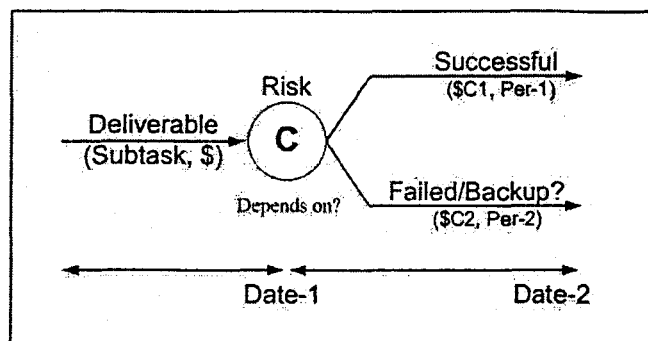

Figure 5-4 – The Deliverable Risk Analysis Tool

5. Conclusion

The MSL Technology Program is tightly coupled to the MSL mission and the MSL milestones. It involves time-critical deliverables that must be developed in time for infusion into the MSL mission. The plan is to reach TRL 6 for each technology by the mission's PDR in 2006. This program transcends the usual gulf between technology and projects by vertically integrating the technology work with pre-project development in a project-like environment with critical dates for technology infusion. The program addresses developing key technology to enable MSL's revolutionary science mission.

6. Acknowledgements

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